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Laser nanostructured Co nanocylinders-Al_2O_3 cermets for enhanced & flexible solar selective absorbers applications

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ABSTRACT

We report on the structural and optical properties of laser surface structured Co nanocylinders-Al_2O_3 cermets on flexible Aluminium substrate for enhanced solar selective absorbers applications. This new family of solar selective absorbers coating consisting of Co nanocylinders embedded into nanoporous alumina template which were produced by standard electrodeposition and thereafter submitted to femtosecond laser surface structuring. While their structural and chemical properties were investigated by X-ray diffraction, scanning electron microscopy, energy dispersive spectrometry and atomic force microscopy, their optical characteristics were investigated by specular & diffuse reflectance. The optimized samples exhibit an elevated optical absorptance $\alpha(\lambda)$ above 98% and an emittance $\varepsilon(\lambda) \sim 0.03$ in the spectral range of 200–1100 nm. This set of values was suggested to be related to several surface and volume phenomena such as light trapping, plasmon surface effect as well as angular dependence of light reflection induced by the ultrafast laser multi-scale structuring.

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1. Introduction

In solar thermal power (CSP) plants, the incoming solar radiation is tracked by a large field of mirrors which concentrate the solar radiations towards a ceramic-metal selective solar absorber nanocoating deposited onto a tubular system. In general, this latter is deposited on steel, aluminium or copper tubular substrates containing the fluid to be heated [1–5]. The function of the selective optical absorber is to transform the incident solar radiations (specifically the Visible part of the solar spectrum) into heat while suppressing heat losses due to thermal emissivity. These two pivotal requirements of an effective selective solar absorber in terms of a maximum absorptance ($\alpha(\lambda)$) of the solar radiations (in the wavelength range from 0.29 to 2.5 μm) and a minimum emittance ($\varepsilon(\lambda)$) in the infrared spectrum (>2.5 μm) are met by choosing specific spectrally selective configurations of the absorber material itself [1–5].

Various configurations can be adopted as summarized in Fig. 1. More precisely, the selective solar absorber coatings can be categorized into 6 distinct families: (i) intrinsic, (ii) semiconductor-metal tandems, (iii) multilayered absorbers, (iv) multi-dielectric composite coatings, (v) textured surfaces, and (vi) selectively solar-transmitting coating on a blackbody-like absorber. Intrinsic absorbers use a material which exhibits intrinsic properties that result in the desired spectral selectivity. Semiconductor-metal tandems absorb short wavelength radiations because of their semiconductor bandgap and have low thermal emittance as a result of the metal layer. Multilayered absorbers use multiple reflections between layers to absorb light while tailored to be efficient selective absorbers. Textured surfaces can produce high solar absorptance by multiple reflections among needle-like, dendritic, or porous microstructures. In addition, selectively solar-transmitting coatings on a blackbody-like absorber are typically used in low-temperature applications. Metal-dielectric composites known as cermets (ceramic-metal nano-composites) which are of interest in this contribution, consist of nano-scaled metal particles in a dielectric or ceramic host material. They are more suitable for high temperature solar photo-thermal applications [6–18].

Within the 6 above mentioned primary configurations of selective solar absorbers, one could consider an additional one. This later, which could be classified between textured surfaces and

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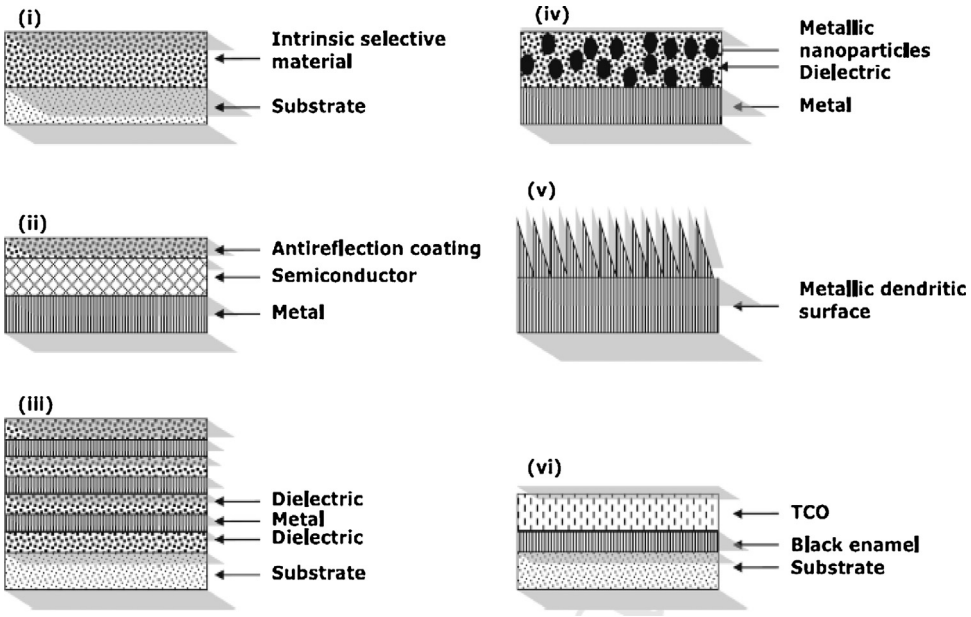

Fig. 1. Standard configurations of the selective solar absorbers for CSP applications: (i) intrinsic, (ii) semiconductor-metal tandems, (iii) multilayered absorbers, (iv) multi-dielectric composite coatings, (v) textured surfaces, and (vi) selectively solar-transmitting coating on a blackbody-like absorber.

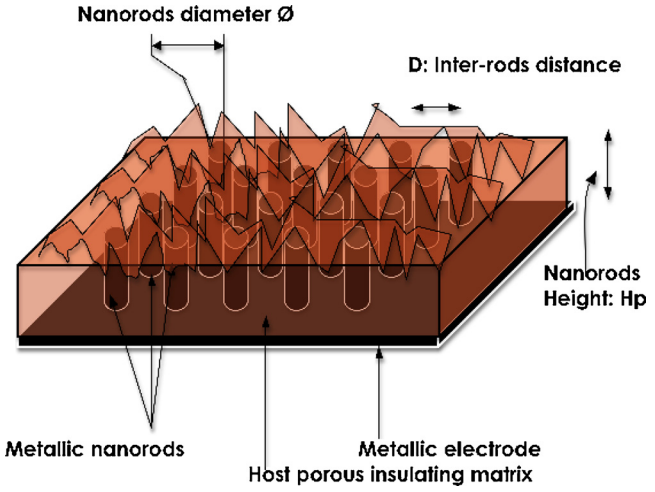

Fig. 2. Schematic configuration of the laser surface structured selective solar absorber consisting of vertically oriended Co nanocylinders electrodeposited in porous Al_2O_3 deposited onto flexible Al sheets.

cermet composites consists of non-percolated aligned tubular metallic nanocylinders embedded in an oxide host matrix with an additional laser surface texturing as depicted in Fig. 2. Yet these nanocylinders based systems have been among the first class of selective solar absorbers if one considers the reported results in the literature dating from late 1980, their femtosecond laser surface nanostructuring enhances further their optical selectivity as shown for the first time in this communication (as per our best knowledge). This later aspect represents the originality of this contribution. The significantly reduced VIS-NIR reflectance observed in the experiments (and hence a high absorptance $\alpha(\lambda)$) due to the additional ultrafast laser surface structuring can result from several absorption mechanisms. These mechanisms that include light absorption due to antireflection and plasmonic effects, trapping of the light in surface cavities and/or Fresnel angular reflection dependence.

This contribution reports on the morphological, structural and enhanced optical characteristics of femtosecond laser surface structured Co nanocylinders-Al_2O_3 selective solar absorbers. Their specific elevated optical absorptance $\alpha(\lambda)$ relatively to classical Co-Al_2O_3 cermets make them attractive for flexible and possible cost effective selective solar absorbers applications.

2. Experimental techniques

The methods that are commonly used to produce nanocylinders in porous host matrices include electrodeposition into nanometer wide porous material/template [19,20]. Molecular sieves, track-etched polymer membranes and porous anodic alumina are typical examples of some of this family of porous materials [21,22]. This established method has attracted much attention because the pore density of the nanocylinders is high, with controllable diameters in addition to the pores uniformity [23–32]. This latter characteristic is capital for magnetic based applications especially in the magnetism for spin transfer phenomena, giant magnetoresistance, magnetic reversal and uniaxial magnetic anisotropy, as well as ferromagnetic resonance [24–29].

In the current study, the ordered porous Al_2O_3 templates are first fabricated from ~1.2 mm thickness Al foil substrates followed by a standard two-step electrochemical anodization process. Each of the Al_2O_3 layers onto non anodized end substrates is first anodized in 0.3 M oxalic acid solution under constant voltage, using a platinum mesh as a cathode (with the initial Al foil as an anode) while the aqueous oxalic acid serving as the electrolyte. The formed oxide layer is removed by acid etching in a mixed solution of 0.4 M phosphoric acid and 0.2 M chromic acid at about ~60 °C. The sample is re-anodized using the same parameters as in the first step, but for a longer time (~6 h). The produced final porous anodic alumina template has pore diameters of about ~41.2 nm with a porosity of the order of ~3.5% (5×10^9 pores/cm^2). The anodizing conditions fix the average values of the average pores' diameter $\langle Ø_{pores} \rangle$, their depth $\langle h_{pores} \rangle$ as well as their centre-to-centre spacing $\langle D_{Intra\text{-}pores} \rangle$ (Fig. 2). For example anodizing Al in 15% oxalic acid at 10 V DC yields pores having a diameter of about 8 nm and an interval distance $\langle D_{Intra\text{-}pores} \rangle$ of around 35 nm. Following the anodization phase, the formed nanopores are open on one end and the other end is attached to the non anodized part of the Al film substrate as schematically shown in Fig. 2. The second phase of the process consists of filling partially or totally the nanopores

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